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A LABORATORY STUDY OF HEAT FLUX THROUGH COASTAL POLYNYAS DURING FRAZIL-ICE PRODUCTION

by

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ABSTRACT

We carried out laboratory experiments with a test tank in a cold room to estimate heat flux through coastal polynyas, which have great effects on climate in the polar regions. The estimation of heat flux from water to air was made with measurements of cooling rate of water temperature and of the rate of ice production as a function of wind speed and water salinity. Both rates increased with increasing wind speed and water salinity. The major factor that governs heat flux is the size of the open water area. In an open water area continuously maintained by a strong cold wind, rapid production of frazil ice and its downwind transport occur simultaneously; so the open water serves as an efficient ice factory. In the case of NaCl solution, supercooled water with salinity greater than 23.1‰ is denser than water at its freezing point. Therefore, the formation and sinking of the supercooled water occur in the persistent open water; this results in great lowering of water temperature and underwater-ice production. Strong wind and high salinity enhance the supercooling effect.

INTRODUCTION

In polar oceans, some open water areas persistently exist within the winter sea-ice cover. Particularly in a coastal region where a strong offshore wind is blowing continuously, vigorous production and downwind transport of ice occur simultaneously. Under such cold, windy conditions, the ice forms rapidly as very small disc-shaped crystals called frazil ice. These crystals measure about 1–4 mm in diameter and 1–100 μm in thickness (Martin, 1981). Hence the open water is maintained by the wind while sea ice forms. These wind-generated open waters, or coastal polynyas, serve as very efficient ice factories, so they are better heat sources than ice-covered areas where the sheet ice grows under calm conditions.

Moreover, as ice forms in sea water, it excludes salt in the form of brine with higher salinity than that of surrounding water. The amount of salt exclusion increases with increasing ice production (Wakatsuchi and Ono, 1983). Therefore large salt fluxes occur in polynya regions. We can suppose that dense saline water resulting from the excluded brine will cause shelf water to become denser. Taking the Southern Ocean as an example, such rapid ice production has been considered to contribute to the formation process of Antarctic Bottom Water (e.g. Gill, 1973). In this way coastal polynyas have a great influence on climate and abyssal circulation in the polar regions.

The present study aims to clarify the process of rapid frazil-ice production in the wind-generated coastal polynyas. This paper mainly describes characteristics of heat flux, or its dependence on wind speed and water salinity, through the polynya accompanied with rapid ice production, on the basis of our laboratory results.

EXPERIMENTAL APPARATUS AND METHODS

Laboratory experiments were performed in a cold room at a set temperature of −10°C. Figure 1 is a diagram of the experimental apparatus. An acrylic test tank of width 0.4 m, length 2 m and depth 0.6 m was filled with NaCl solution or fresh water. The sides and base of the tank were covered with styrofoam for heat insulation, so that the inner water could be cooled only from the upper surface. After the whole water layer was cooled to its freezing point, an artificial wind was continuously blown over the water surface from one side with an air blower. We then observed the following phenomena. Numerous frazil-ice crystals were produced in the open water and transported downwind. At the downwind end, the crystals accumulated in a layer, then advanced laterally in the upwind direction with time, so the open water area gradually decreased. Such a process has been also shown in the calculated results of a numerical model presented by Bauer and Martin (1983).

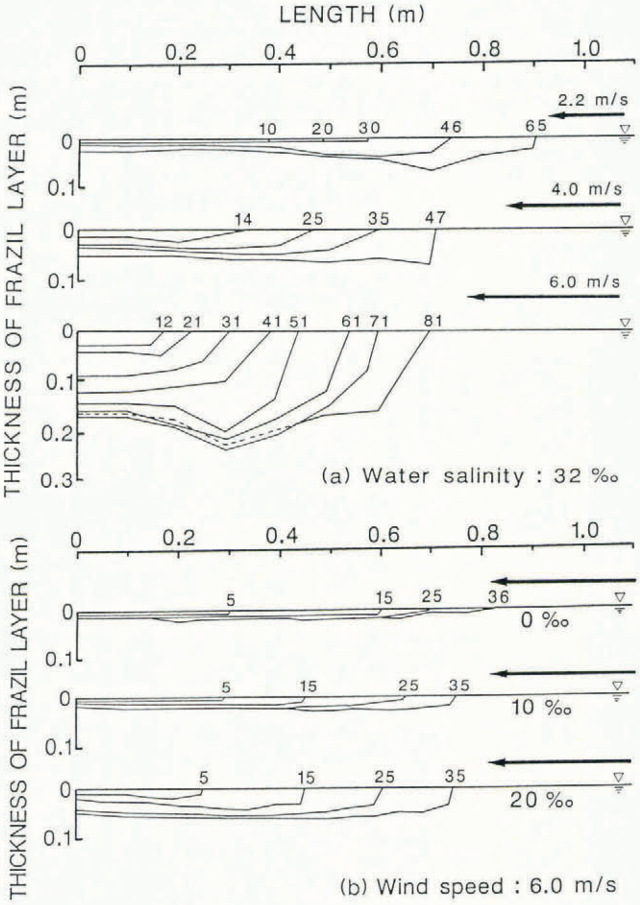

Fig. 1. Schematic diagram of the experimental apparatus set in a cold room.

Each experiment was run under various conditions. Wind speed was varied between 2 and 6 m s^{-1}, and the water salinity between 0 and 34‰. To estimate the rate of frazil-ice production, we measured the following items at regular time intervals: edge position, thickness, and salinity

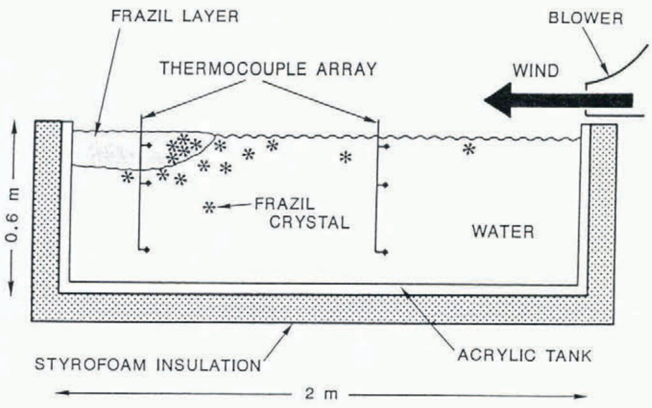

Fig. 2. Cross section of the frazil-ice layer accumulated on the lee. Wind is blowing from the right. Contour values above the water surface give the elapsed time in minutes. (a) Three cases with different wind speeds and constant water salinity of 32‰. (b) Three cases with different water salinities and constant wind speed of 6.0 m s^{-1}.

of the accumulated frazil-ice layer. Water temperature was also continuously recorded with copper-constantan thermocouples.

RESULTS

Production and accumulation of frazil-ice crystals

For the case described above, Figure 2 shows the time variations of the cross section of the accumulated frazil-ice layer. The accumulation pattern changes with both wind speed and water salinity. In the case of a fixed water salinity of 32‰, at higher wind speed a thicker layer formed. Especially at wind speed of 6.0 m s^{-1}, the layer thickness increased rapidly with time (Fig. 2). This was caused by the production of underwater ice, which took the shape of fine dendritic crystals. On the other hand, for water salinities less than 30‰, relatively large disc-shaped crystals formed near the water surface, and the thin accumulation layer covered the surface faster than with water salinity of 32‰ (Fig. 2b). As shown in Figure 3, the rate of decrease of open water area decreased with increasing water salinity; that is, at higher salinity a large open water area was maintained for a long period of time, so that a large amount of heat was released from the water. It was also found that the production rate of frazil ice increases with wind speed and with water salinity. In our experiments, for wind speed of 6.0 m s^{-1} and salinity of 32‰, the rate of frazil ice production gives 5–6 × 10^{-3} kg m^{-2} s^{-1}, which is about four to five times greater than that of sheet ice growing vertically (Ushio and Wakatsuchi, 1989). These results imply that, in the polynya region, the heat flux from the water to the air increases with the large amount of ice production.

Estimation of heat flux during ice production

We estimated the heat flux from the water to the air. The heat exchange between the water and air is expressed by

$$Q_t + M_w C(dT/dt) - L(dM_i/dt) = 0, \qquad (1)$$

where Q_t is the total heat flux to the air, M_w is water mass, C is the specific heat of the water, (dT/dt) is the rate of decrease of the water temperature, L is the latent heat of fusion, and (dM_i/dt) is the rate of frazil-ice production. A positive Q_t denotes a heat loss from the water to the air. The second and third terms in Equation (1) are calculated from the time variation of the water temperature and the rate of ice production, respectively (Ushio and Wakatsuchi, 1989). Then the total heat flux Q_t is calculated as a remainder term. Figure 4 shows the average heat flux during each experiment as a function of water salinity and wind speed. Heat flux increased as the water salinity increased, with a particularly large increase occurring for the jump from a 20‰ salinity to a 32‰ salinity under conditions of high wind speed (6.0 m s^{-1}). According to Figures 2 and 4, it is found that a great heat flux causes vigorous production of frazil ice.

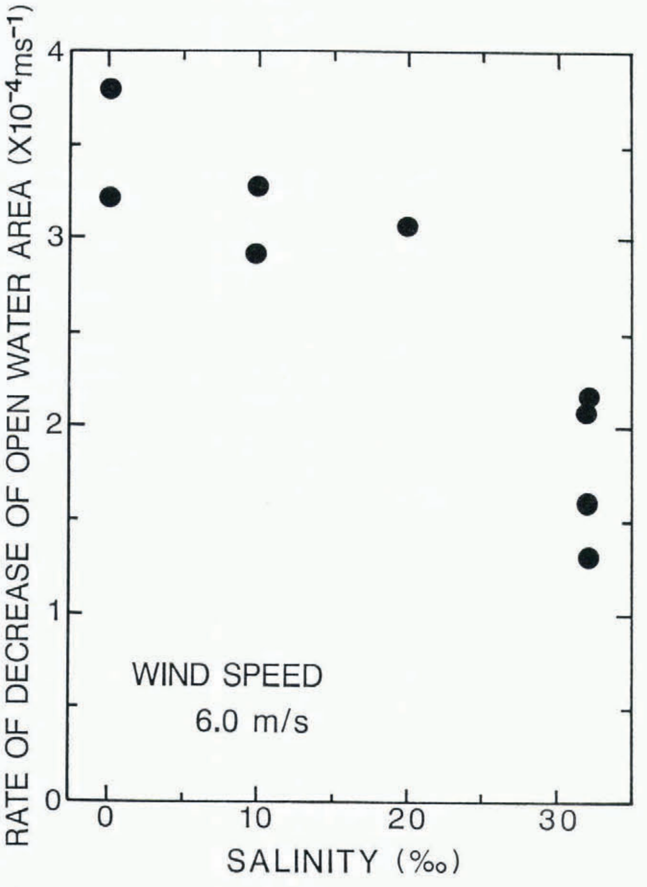

Fig. 3. Rate of decrease of open water area vs. water salinity.

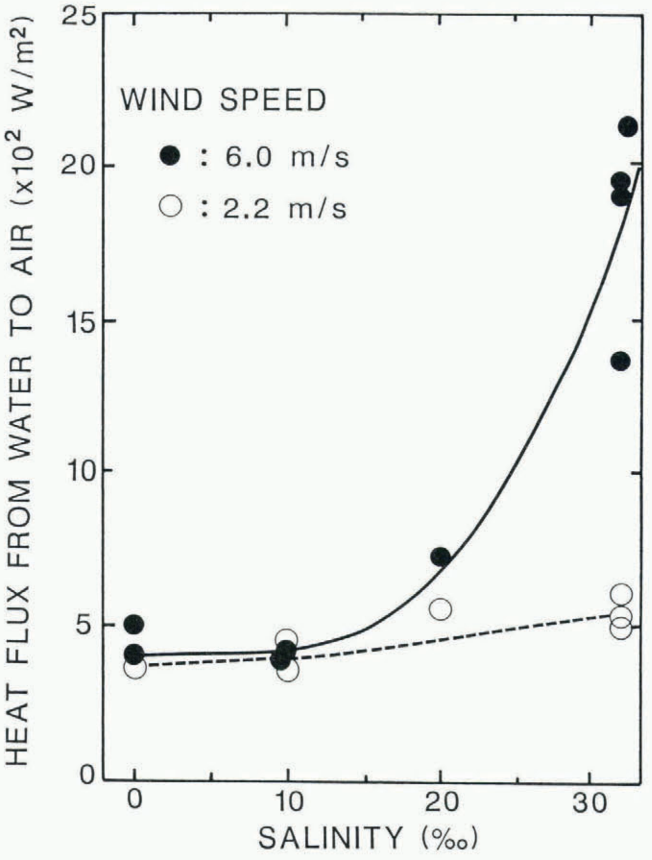

Fig. 4. Average heat flux from water to air as a function of water salinity for two different wind speeds.

DISCUSSION

We next consider the factor that governs heat flux through the wind-generated open water. As sea water cools and freezes, vertical convection induced by atmospheric heat loss plays an important role. For salt water with a salinity greater than 23.1‰, the temperature of maximum density (T_m) is lower than the freezing point (T_f) of the water, so that thermal convection continues up to the time at which freezing starts. It is found that convection can also be induced by the formation of supercooled water, which is heavier than water at its freezing point. As for salt water with a salinity less than 23.1‰, T_m is higher than T_f, so that the fluid is stable even after the temperature reaches its freezing point. Therefore thermal convection cannot occur during the cooling period of the less saline water. Natural sea water has the same density properties as NaCl solutions.

The ratio of latent heat flux due to ice production to total heat flux is shown in Figure 5. The ratio increases with increasing water salinity. This tendency results from the rapid underwater-ice production induced by a large amount of supercooled water which is stored in a lower layer; the degree of supercooling gave 0.1–0.2° as maximum value in our laboratory results. It is considered that formation and maintenance of the supercooling state bring about copious frazil-ice production under water, so that the ratio of latent heat flux increases.

The density effect is clearly exhibited with the stronger wind (Fig. 4); that is, supercooled water which forms on the water surface is effectively transported to the bottom through the wind-driven flow as well as by instability in density. As a result, the water was supercooled to a certain depth and vigorous production of frazil ice occurred under water. Therefore, the open water area is maintained for a long time and causes great heat flux from the saline water in spite of the vigorous ice production under cold windy conditions.

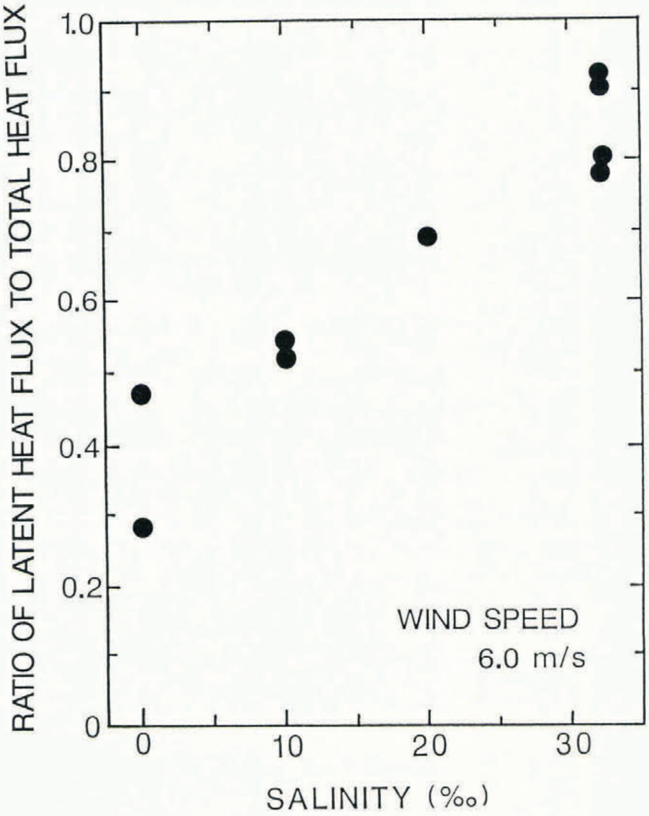

Fig. 5. Ratio of latent heat flux due to ice production to total heat flux, plotted as a function of salinity.

CONCLUDING REMARKS

Our laboratory experiments have clarified the characteristics of heat flux through coastal polynyas. Heat flux from water to air increased with increasing wind speed and water salinity. The major factor that governs the heat flux lies in the maintenance of open water areas. The strong wind causes an efficient ice production in maintaining the open water area. In case of NaCl solution with salinity above 23.1‰, the supercooled water appears to sink into the lighter water which is at freezing point. In the persistent open water area, therefore, the wind-driven circulation efficiently transports the supercooled water which forms on the water surface to the deep layer; this results in both supercooling at depth and underwater-ice production. These laboratory results suggest that great heat flux possibly occurs in wind-generated coastal polynyas.

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